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Pathways toward zero-carbon electricity required for climate stabilization

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HIGHLIGHTS

- We compile the carbon content of electricity in published IPCC projections.
- All models agree: climate stabilization requires near-zero carbon electricity.
- All considered countries decarbonize electricity under every climate stabilization target.
- This finding is robust to the unavailability of technologies such as nuclear and CCS.
- Electrification (e.g., electric cars) makes sense within a long-term strategy.

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ABSTRACT

This paper provides pathways of the carbon content of electricity extracted from the Intergovernmental Panel on Climate Change's fifth Assessment Report scenarios database. It demonstrates three policy-relevant aspects of the carbon content of electricity that are implicit in most integrated assessment model results but under-discussed in academia and the policy debate. First, climate stabilization at any level from 1.5 °C to 3 °C requires the carbon content of electricity to decrease quickly and become almost carbon-free before the end of the century. As such, the question for policy makers is not whether to decarbonize electricity but when and how to do so. Second, decarbonization of electricity is still possible and required if some of the key zero-carbon technologies—such as nuclear power or carbon capture and storage—turn out to be unavailable. Third, progressive decarbonization of electricity is part of every country's cost-effective means of contributing to climate stabilization. The pathways of the carbon content of electricity reported here can be used to benchmark existing decarbonization targets, such as those set by the European Energy Roadmap or inform new policies in other countries. They can also be used to assess the desirable uptake rates of electric and plug-in hybrid vehicles, electric stoves and heat pumps, industrial electric furnaces, or other electrification technologies.

1. Introduction and literature review

Power generation plays an important role in global warming for at least two reasons. First, it is responsible for a large share of anthropogenic greenhouse gas (GHG) emissions: today's electricity accounts for almost 14 GtCO2/year, about 29% of total annual greenhouse gas emissions. Reducing the carbon content of electricity would thus decrease global GHG emissions significantly. Second, electricity can be used as a substitute for carbon-intensive fossil fuels in many cases. For instance, direct energy consumption for transportation and housing together represent about 30% of total emissions from energy; and industrial energy consumption, mainly used to produce heat or motion, accounts for an additional 19% [1,2]. Technologies such as electric vehicles, heat pumps, electric furnaces, industrial motors and other electric equipment could in part replace fossil-fuel based counterparts in these sectors, reducing indirectly GHG emissions.

An increasingly consensual result from prospective models is that both decarbonization of electricity supply and electrification of the energy system play a decisive role in reaching climate stabilization [3–14]. Indeed, stabilizing climate change to any level (e.g. 1.5, 2, or 3 °C) requires reducing global net emissions to zero [15–18]. Moreover, switching from fossil fuel to low-carbon electricity is one of the few technical options available to drastically reduce GHG emissions in energy-intensive sectors such as industry, transportation and buildings.

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Despite this consensus and its importance to inform the policy debate, we are not aware of any study that publishes pathways of the future carbon content of electricity consistent with climate stabilization. For instance, while decarbonization of the power sector is implicit in all of the above-mentioned studies, none of them explicitly reports the pathways of the carbon content of electricity.

To fill this gap, this study estimates the carbon content of electricity in a set of existing emission-reduction pathways, and makes those estimates available to decision-makers, researchers in other disciplines, and the public. It reports pathways at the global level, and at the country/region level for Brazil, China, the EU, India, Japan, Russia, and the USA. It also considers a variety of assumptions regarding availability of technology and the ambition of long-term climate targets.

These pathways of the carbon content of electricity may be useful to planners and policymakers designing climate mitigation strategies. They provide a reference on the speed at which decarbonization of the power sector could happen to meet a given climate target. They may thus be used to benchmark existing milestones, such as the ones proposed by the European Commission's energy roadmap [19], the Clean Power Plan that was recently under discussion in the US, or Mexico's ambitious GHG targets [20,21]. These trajectories can further inform new plans in other countries or jurisdictions.

Second, such pathways of the carbon content of electricity are useful to assess the long-term desirability of specific electrification technologies. Indeed, without access to pathways of the carbon content of electricity consistent with climate stabilization, existing studies have focused on the impact of electrification on *current* GHG emissions. For instance, electric vehicles have been found to cause more GHG emissions than conventional vehicles if they are charged in places where, or at time of the days when, electricity is mostly produced from coal [22,23,19,24–30]. This finding has been often taken as an argument that electrification is to be avoided [31]. Similar results have been reported on industrial electric furnaces [32], and buildings [33–35].

Yet, to inform energy and industrial policy, the important question might not be what would be the impact of electrification technologies in the year when they are implemented, but rather whether the adoption of such technologies is consistent with a long-term decarbonization strategy [36,16,37].[1] With transparent pathways of the carbon content of electricity, scholars and analyst from any discipline will be able to leverage results from the IAM community to perform an *integrated life cycle analysis* [40,41]. These pathways can also give a basis to evaluate the impact on GHG emissions of technologies or industrial processes that are too specific to be explicitly represented in an IAM. This paper demonstrates this usage by assessing the desirability of electric cars as an emission-reduction measure in six different regions of the world.

The paper proceeds as follow. The methodological approach is detailed in Section 2. Section 3.1 presents and discusses global pathways of the carbon content of electricity in climate-stabilization scenarios, showing that under the most technology-optimistic assumptions, bioenergy combined with carbon capture and storage (BECCS) allows for producing electricity with negative carbon emissions. Section 3.2 reports pathways in scenarios with constrained deployment of either (i) both nuclear and CCS or (ii) renewable power. In both cases, the carbon content of electricity is still projected to decrease to near-zero levels. Section 3.3 shows that this reduction to near-zero levels of emissions in the power sector occurs in every region of the world represented in IAMs. Finally, Section 3.4 develops an example of how these pathways can be used to assess the relevance of promoting electric cars to reduce carbon emissions. Section 4 discusses the findings and concludes. The Appendix A details pathways at the country/region level, for Brazil, China, the EU, India, Japan, Russia, and the US under different scenarios.

2. Methods

This study uses two main datasets. The first one, AMPERE, comprises a set of 68 pathways generated with 12 different integrated assessment models (IAM) for the purpose of a recent comparison study [42].[2] These pathways cover both the local and global level. For further insights on a global level, we analyze the full IPCC AR5 database of 274 scenarios generated with 56 IAMs [45].

IAMs compute pathways of the socio-economic and energy systems under the constraint set by climate targets. IAMs factor in a wide range of parameters, such as long-term demographic evolution, availability of natural resources, and countries' participation to emission-reduction efforts. Technology costs and maximum penetration rates, in particular, are calibrated using a mix of historical uptake rates and assumptions on learning by doing and autonomous technical progress [46,47].

The methods used to derive pathways vary across IAMs [48]. For instance, some models use intertemporal optimization to assess the least-cost investment and operation plan consistent with a climate target. Others start from a target emission pathways, solve recursively for the carbon price that would deliver the emission target at each time step, and derive investment and operation decisions consistent with the resulting carbon price. IAMs are regularly peer-reviewed in comparison exercises [49,50,48,51,52] and occasionally evaluated against historical data [53,47].

In this study, carbon intensity is defined as CO2 emissions (gCO2) per unit of electricity produced (kWh). Electricity production is restricted to secondary energy/electricity, that is, the total electric energy produced by the power sector, excluding that used by the power supply sector itself for transformation, transportation and distribution (including these losses would result in lower carbon intensities). This carbon intensity measure is then constructed by dividing carbon dioxide emissions from electricity generation by total electricity generation per scenario, model, region, and time step.

Two kinds of limitations should be mentioned in interpreting the results of this study: first, the study is restricted to a subset of IAM trajectories, which may introduce biases; and second, IAMs may imperfectly represent barriers to power generation decarbonization.

The first limitation applies because a subset of IAM trajectories is selected based on the results reported in the IPCC's AR5 and the AMPERE database, because the data is publicly available in the required granularity. Comparing the figures in the main text to Fig. 14 in the Appendix A shows that the findings from AMPERE are consistent with the wider IPCC database of decarbonization pathways [45]. Nonetheless, previous studies have documented the risk of selection bias in IAM reviews, as results are not always reported when targets are unachievable [54]. The sample of trajectories considered here may be affected by selection bias, given some models might not report their results with some generation technologies unavailable. For instance, when availability of some technologies is restricted, such as CCS and nuclear, the number of reported paths decreased, when targeting 450 ppm CO2-eq (this effect is mitigated with the looser 550 ppm CO2-eq constraint).[3] This hints at the potential difficulty of reaching a stringent climatic target if the development of BECCS is constrained [55–57].

The second limitation comes from the fact that IAMs might imperfectly account for several barriers to the decarbonization of power

[1] Electrification also comes with associated health benefits in regions that heavily rely on coal for power generation, see Peng et al. [38]. Assessing how changes in the energy system impacts air quality is another recent application of IAMs, see Shi et al. [39].

[2] We chose this study as it is freely available online [43], other recent studies such as EMF27 [44] are of similar scope, use a broader variety of models and assumptions, and reach qualitatively and quantitatively similar results, but are unfortunately currently not publicly available online in the required granularity.

[3] Such evidence should be taken with caution, as participants were not required to run every scenario (scenarios were ranked as required, recommended, or optional). A smaller number of trajectories does not necessarily reflect selection.

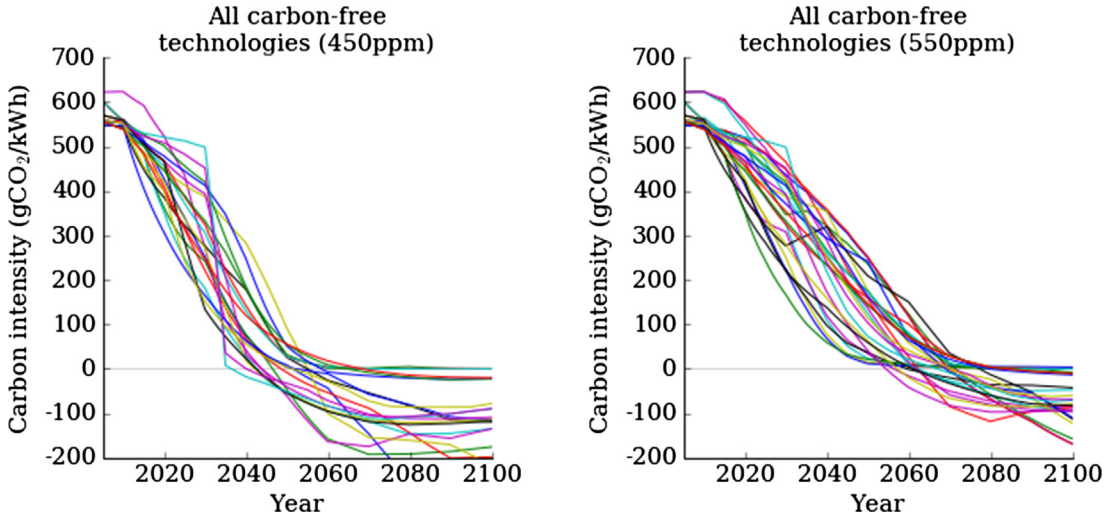

Fig. 1. Carbon content of electricity at the global scale in two scenarios: (left) 450-ppm stringent GHG concentration target (consistent with +2 °C); (right) 550-ppm less stringent GHG concentration target (consistent with +2 to 3 °C). Each thin line corresponds to the pathway simulated by one integrated assessment model (the reported carbon intensity for 2005–2010 varies among IAMs because they use different scopes and sources of historical data for calibration). In both cases, bio-energy with carbon capture and storage (BECCS) allows to reduce the carbon content of electricity to below-zero levels by the end of the century.

generation [46]. With a large penetration of intermittent renewable energies, ensuring the stability of the power system could require substantial investments that may not be accurately captured by IAMs [58]. Also, some low-carbon technologies may require building wider distribution and transmission networks to connect remote energy sources or production locations to end-users (renewable energies and nuclear) and transportation infrastructure to carbon sequestration sites (CCS). Finally, building public acceptance for a new technology, such as CCS, can further delay or prevent adoption [59].[4]

Despite these limitations, this methodology allows to highlight a consensus within the IAM community about the need for reaching zero-carbon electricity before the end of the century to meet climate-stabilization targets. This study also makes the numbers behind this consensus available to a wide community.

3. Results

3.1. Climate stabilization requires zero-carbon electricity

For the AMPERE study, IAMs were run under the constraint that final GHG atmospheric concentration should not exceed 450-ppm CO2-eq—Meinshausen et al. [61] estimate such concentration leads to a 63–92% probability of remaining below +2 °C by 2100. Fig. 1 presents the projected carbon intensities of the global electricity generation in different models for this scenario. It shows that all models project a drastic decrease in carbon intensity by the end of the century, with most of them reaching net-zero between 2040 and 2060.

Most trajectories in this scenario fall below zero-carbon electricity. In-deed, this scenario assumes that the technologies able to generate low-carbon electricity are widely available—such technologies include mainly wind, solar, hydro, biomass, nuclear and carbon capture and storage [62].[5] Among them, bio-energy with carbon capture and storage (BECCS), the burning of biomass in power plants in connection with the long-term storage of resulting CO2 emissions, allows to produce electricity with negative net GHG emissions [51,57].[6] When BECCS is available, the least-cost strategy to achieve global carbon neutrality is to eventually generate negative-emission electricity thereby offsetting previous overshoot emissions or emissions from other sectors of the economy that are more difficult to decarbonize.

Stabilizing GHG concentration around 450 ppm would require efforts by all countries at a level that may be difficult to achieve in time [64–66]. AMPERE considered the effect of a less stringent concentration target: 550-ppm CO2-eq—generally admitted to be consistent with a +2 to 3 °C warming, and still reasonable probability of remaining below +2 °C [61]. If low-carbon technologies are still assumed to be widely available, pathways to this easier climate target also entail a decrease of the global carbon intensity to negative levels (Fig. 3b).

The large-scale feasibility and desirability of BECCS is controversial, given the potential impact on land use, food production, freshwater availability, and the uncertain availability of suitable geological storage sites [67,68]. These aspects were not fully considered in AMPERE. The next section shows, however, that BECCS is not a pre-requisite for near-zero carbon electricity generation in the second part of the 21st century.

3.2. Near-zero-carbon electricity does not require all carbon-free technologies to be available

One scenario in AMPERE sets a 550-ppm CO2-eq stabilization target and assumes no further deployment of nuclear power after existing plants are decommissioned (for instance for social acceptability reasons) and assuming CCS never reaches market deployment. The decrease in carbon intensity of electricity holds at the global level under these assumptions (Fig. 2). The trajectories in this sample exhibit an average of more than 95% reduction in carbon intensity, reaching less than 50 gCO2/kWh by 2100, while only one outlier pathway does not fall below 100 gCO2/kWh.

AMPERE also explored scenarios where CCS and nuclear are widely available, but renewable energy technologies (biomass, wind and photovoltaic power technologies) are constrained. Fig. 2 reports the pathways of the carbon content of electricity in this case—they still decrease to near-zero or even negative levels by the end of the century.

3.3. Decarbonization of electricity generation happens in all modelled countries or regions

According to pathways in AMPERE (which includes data at country

[4] Public opinion may be even more reluctant to back more ambitious geo-engineering decarbonization technologies. However, such technologies are not modelled in traditional IAMs, see Anasis et al. [60].

[5] The optimal technology mix may also depend on environmental factors beyond the limitations of CO2 emissions, such as air or water quality [63].

[6] Plants extract carbon dioxide from the atmosphere as they grow.

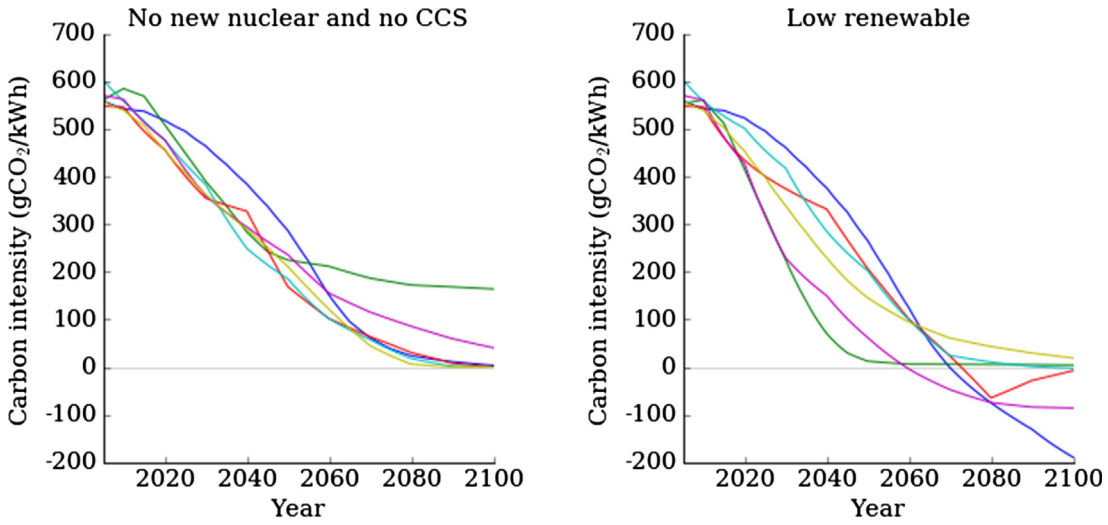

Fig. 2. Decarbonization of global electricity in two 550 ppm scenarios (consistent with +2 to 3 °C): (left) without new nuclear or carbon capture; (right) with low potential for renewable power. In both cases, the carbon content of electricity is reduced to near- or below-zero levels by the end of the century.

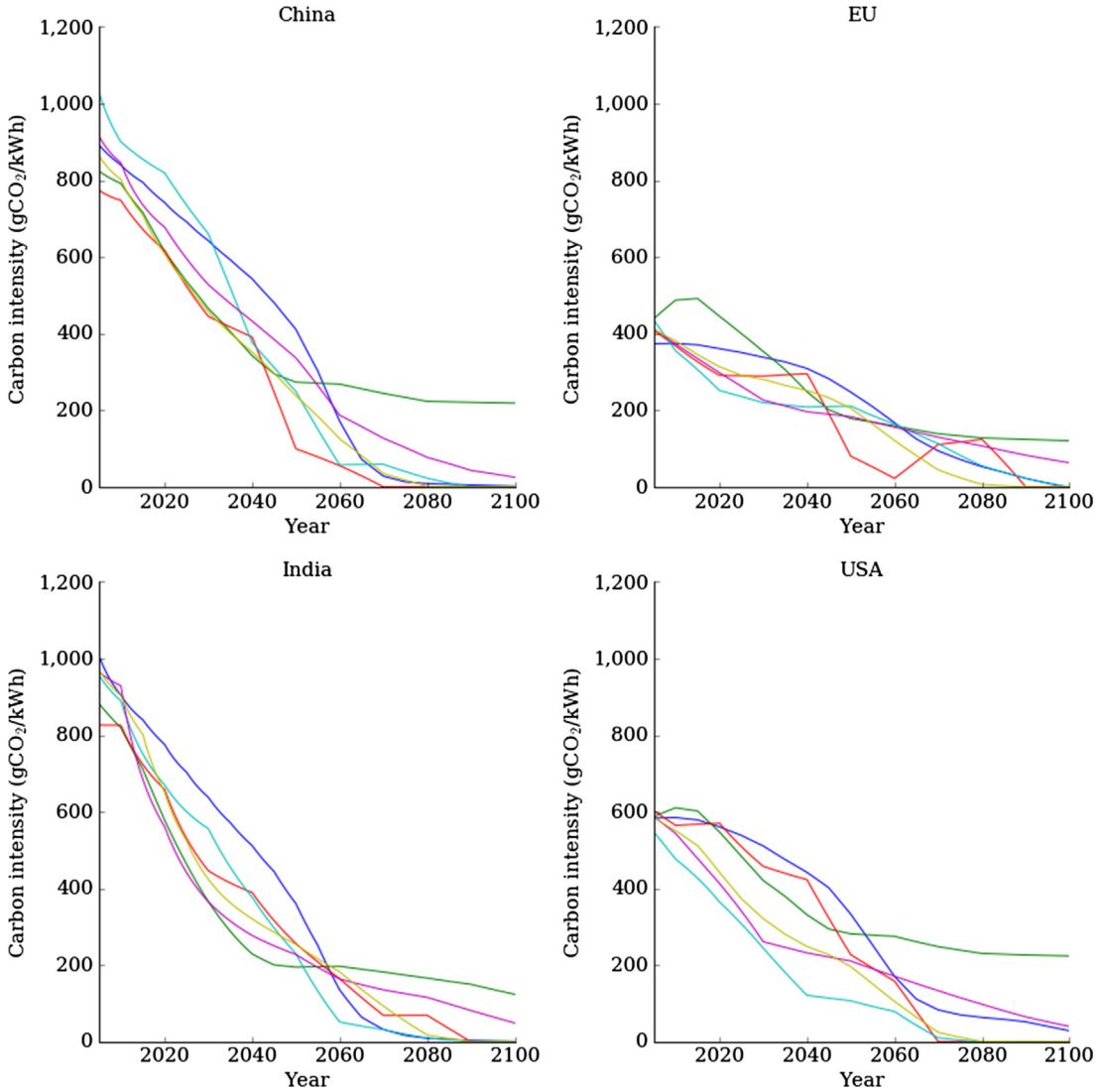

Fig. 3. Carbon intensity in China, Europe, India and the US in AMPERE's 550 ppm (consistent with +2 to 3 °C), technology-pessimistic (no nuclear, no CCS) scenario.

or regional level), a decrease in the carbon content of electricity is feasible in every region of the world. Fig. 3 reports the pathways towards carbon free electricity as simulated in AMPERE for China and India, two countries with high initial emissions from power generation, and for the EU and US, where electricity is already less carbon-intensive.

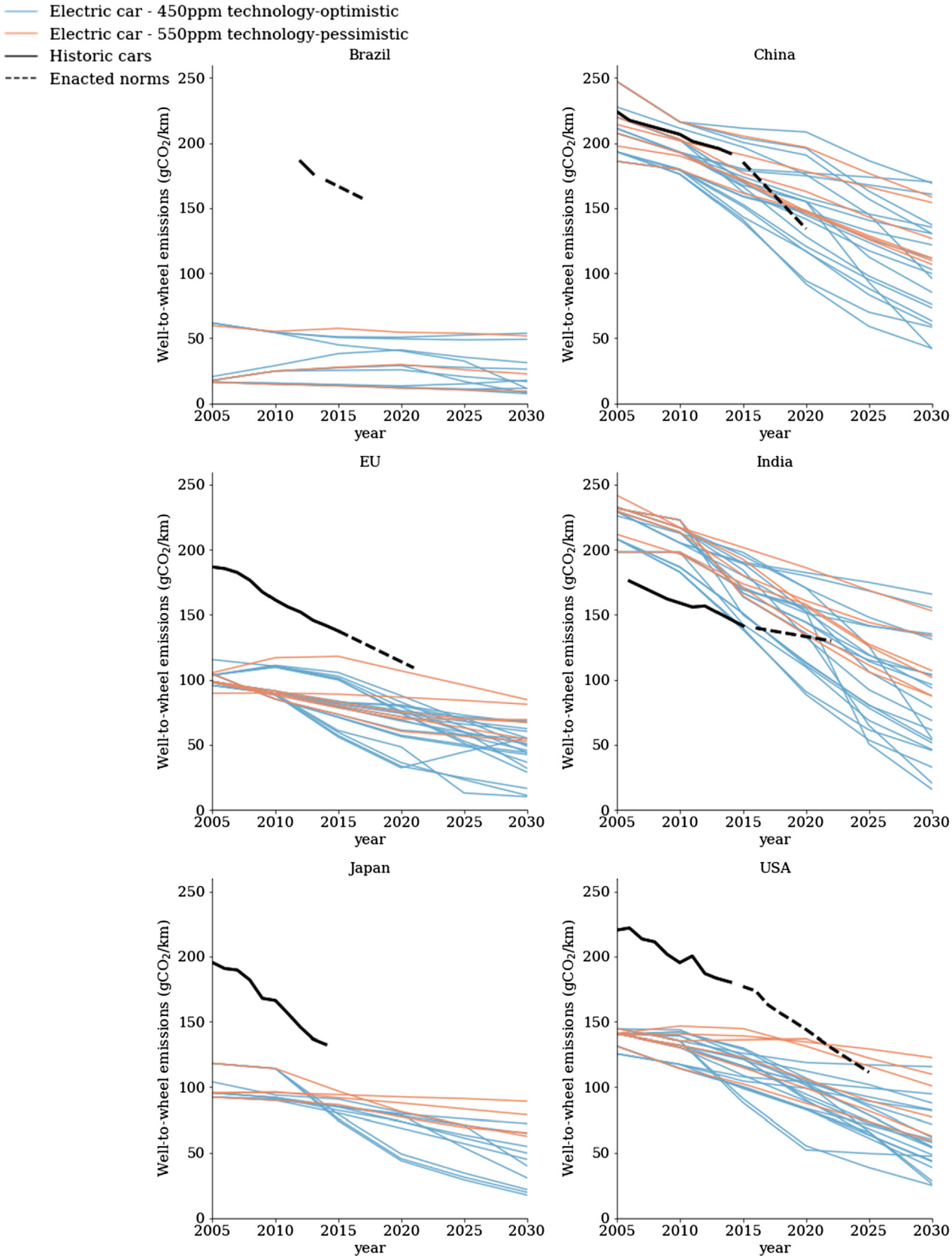

Fig. 4. Well-to-wheel emissions of electric vehicles computed against pathways of the carbon content of electricity extracted from AMPERE and well-to-wheel emissions of an internal combustion engine vehicle fulfilling the maximum emission norms in its jurisdiction computed against Yang and Bandivadekar [69].

Here, the scenario that is least favourable to low-carbon electricity is considered, both in terms of the concentration target (550 ppm) and in terms of technology availability (no replacement of nuclear capacities and no CCS allowed). In every region, the average carbon intensity decreases steadily during the 21st century, and falls below 100 gCO2/kWh in 2100 in every simulation. Detailed pathways for these

regions with different technology portfolios are displayed in the Appendix A.

These figures suggest that electrification is an effective option to reduce long-term emissions in every region. In other words, the policy-relevant question is not whether to electrify, but when and how to do so, as discussed in the next section.

3.4. Application to the assessment of electric vehicles as an emission reduction measure

In this section, we assess the relevance of electric vehicles as a GHG emission reduction policy based on the pathways for the carbon intensity of electricity described above. Whether electric vehicles reduce GHG emissions depends on the carbon intensity of the vehicles they replace, and on the carbon intensity of electricity used to fuel them.

We calibrate the carbon intensity of baseline vehicles based on existing and enacted standards on energy efficiency (such as the CAFE standards in the US) or carbon emissions (such as the NEDC standards in Europe) of new personal cars. Yang and Bandivadekar [69] provide a harmonized global database of these norms, converted into comparable equivalent norms of carbon emissions at the tailpipe, measured in gCO2/km. Six of the jurisdictions covered in the AMPERE database also have norms for new vehicles: Brazil, China, EU, India, Japan, and USA.

The carbon intensity of electric vehicles is taken from a review by the US Environmental Protection Agency [70], which gathers data on electric vehicles for sale in the US. Both the median and the mean electric car consume 20 kWh/100 km. A simple way to assess well-to-wheel emissions of electric vehicles is to multiply their energy consumption and the current carbon content of electricity in different places. However, rather than reducing carbon emissions immediately, the point of promoting a switch to electric mobility is to put the economy on track towards a transition to zero carbon [37]. The effectiveness of doing so will depend not only on the current, but also on the future carbon content of electricity [3].

Here, future emissions from electric vehicles are assessed using the carbon content of electricity in the AMPERE 550 ppm technology-pessimistic scenarios (this is the worst-case scenario for electric vehicles) and the 450 ppm technology-optimistic scenarios (the best-case scenario). The resulting figures are compared to the emission norms for new vehicles in each jurisdiction. To be consistent in the computation of well-to-wheel emissions, 15% is added to the norms to account for losses in refining and transportation of fuel, and 20% to electric vehicles emissions to account for transformation, distribution and recharging losses, following [71].

Fig. 4 shows the result of this analysis. In Brazil, EU, and Japan, the carbon content of electricity is already low enough for electric vehicles to reduce emissions compared to the average vehicle that would just comply with the norm. In all climate-stabilization scenarios considered here, the carbon content of electricity would stay stable or decrease over time. In all the projections and according to all models, the results suggest that electric vehicles would emit less carbon emissions than the norm over the next couple of decades.

In India, the situation is more nuanced. The carbon content of electricity is currently too high for electric vehicles to emit less carbon dioxide than conventional fuel vehicles fulfilling carbon emission norms on average over the country. Only if the carbon content decreases as fast as in the most optimistic models projection, would electric cars reduce emissions by the middle of next decade. Note that switching to electric vehicles *en masse* will likely take more than 10 years, and the government of India may have policy instruments at its disposal to enforce that the carbon content of electricity decreases as fast as in the most optimistic scenarios compiled in AMPERE. This suggests that a well-designed and properly enforced integrated power-transport strategy in India could ensure that electric vehicles are used to reduce emissions over the next decade.

In China, the situation is similar to India, but starting from diverging views on the current carbon content of electricity across models. This may reflect different data sources used by modellers. Notably, the "model uncertainty" on the current carbon content of electricity in China seems smaller than the modelled possibility range for 2030, suggesting again that policy choices today shape the relevance of electric vehicles as climate mitigation tools for the next decades. In this case, no definitive answer to the relevance of electric vehicles emerges from this exercise, which only assesses possible impacts on carbon emissions. Other reasons to adopt electric cars may be appealing to China, such as industrial policy objectives and clean air objectives at the city level.

Finally, in the USA the average carbon content of electricity today is clearly low enough for electric vehicles to outperform carbon dioxide emission standards. However, if standards for new vehicles keep tightening over time, electric cars will only remain below the standard if the carbon content of electricity decreases in a fashion consistent with the 450 ppm scenarios, or as fast as it does in the more optimistic 550 ppm scenarios.

4. Discussion and conclusion

The pathways towards clean electricity reported here should be interpreted cautiously. They do not entail any normative prescription of the level of efforts that any specific country should affect to climate change mitigation. What they show is a consensus among state-of-the-art integrated assessment models: cost-effective climate stabilization requires near-zero carbon electricity in every major country/region of the world. This robust finding is a technical one, which disregards any consideration of the burden sharing of emission reductions: independently of who is or should be paying for it, the cheapest strategy to achieve climate stabilization includes decarbonization of the power supply.

Specifically, this paper has established that (1) all pathways consistent with global warming anywhere from 1.5 °C to 3 °C feature near-zero-carbon electricity before the end of the century; (2) near-zero-carbon electricity can be achieved even if some of the key low-carbon technologies (nuclear, carbon capture and storage, or renewable power) turn out to be unavailable; and (3) near-zero-carbon electricity can occur in every major country or region of the world.

The pathways of the carbon content of electricity reported here can be used outside the community of integrated assessment. As an example, the desirability of electric vehicle as a technology reducing GHG emissions was assessed based on these pathways. More generally, they can be used to inform the design of long-term emission reduction strategies.

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Appendix A. Additional figures

See Figs. 5–14.

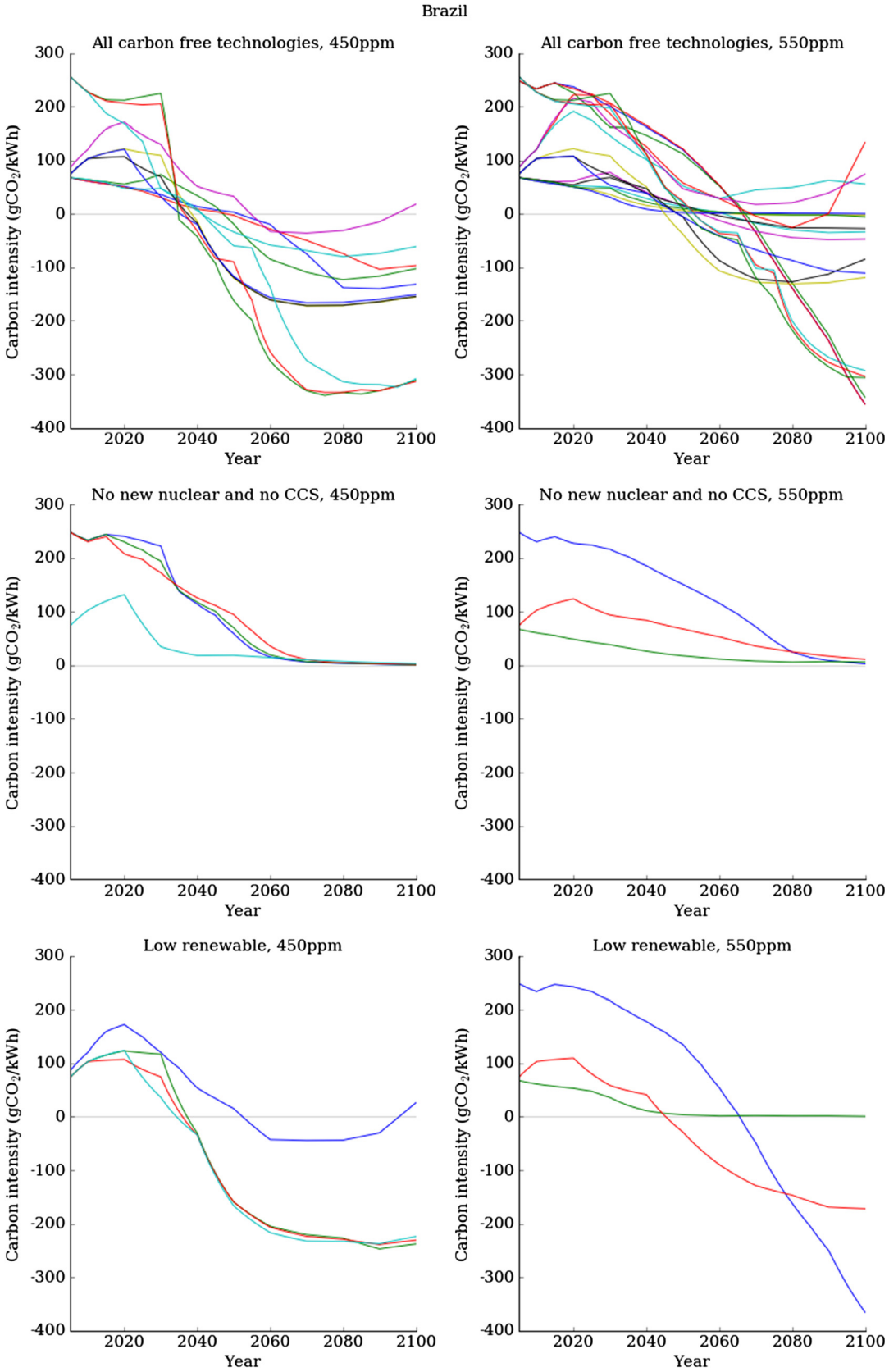

Fig. 5. Carbon content of electricity under in Brazil (AMPERE database).

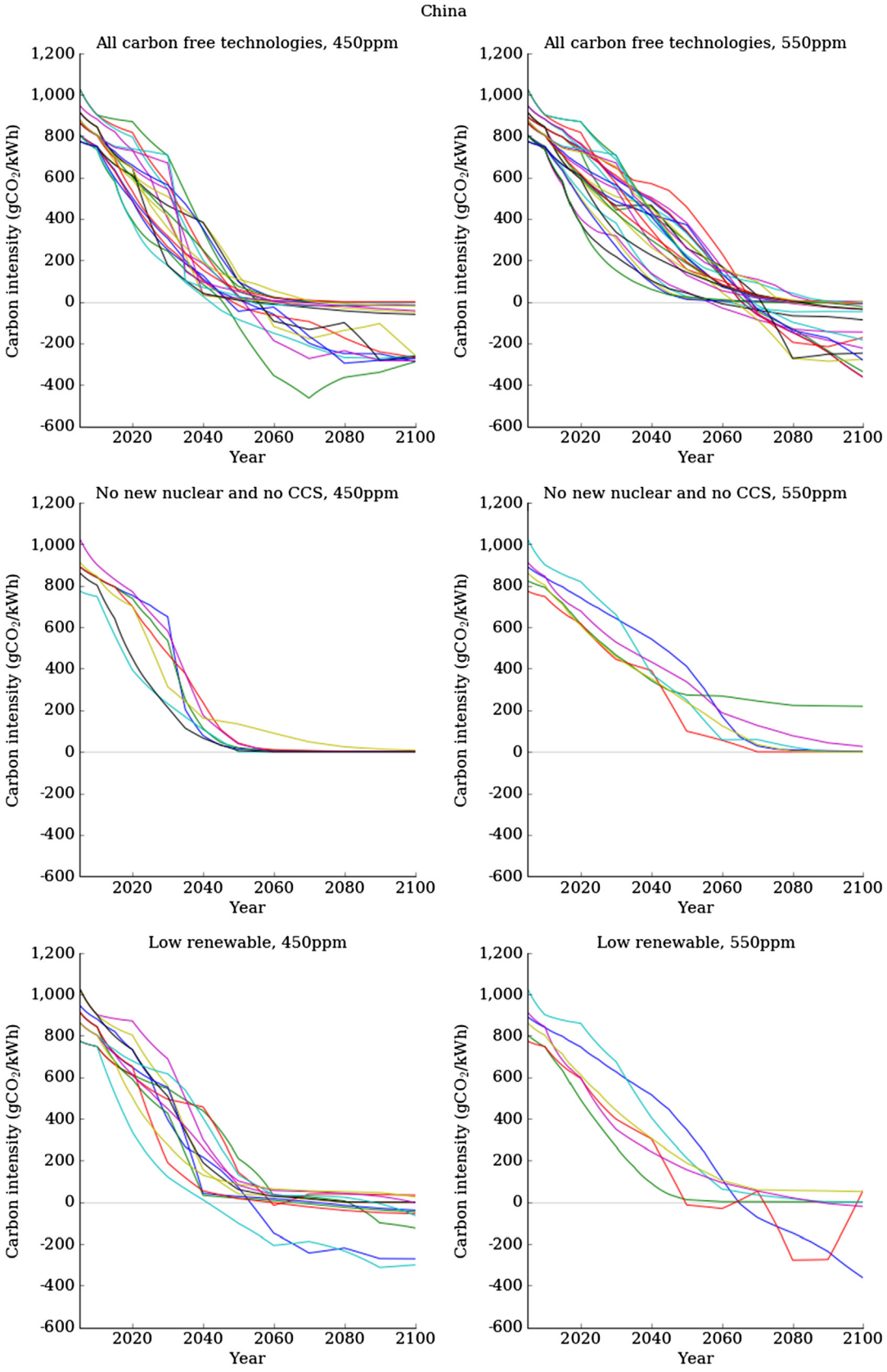

Fig. 6. Carbon content of electricity in China (AMPERE database).

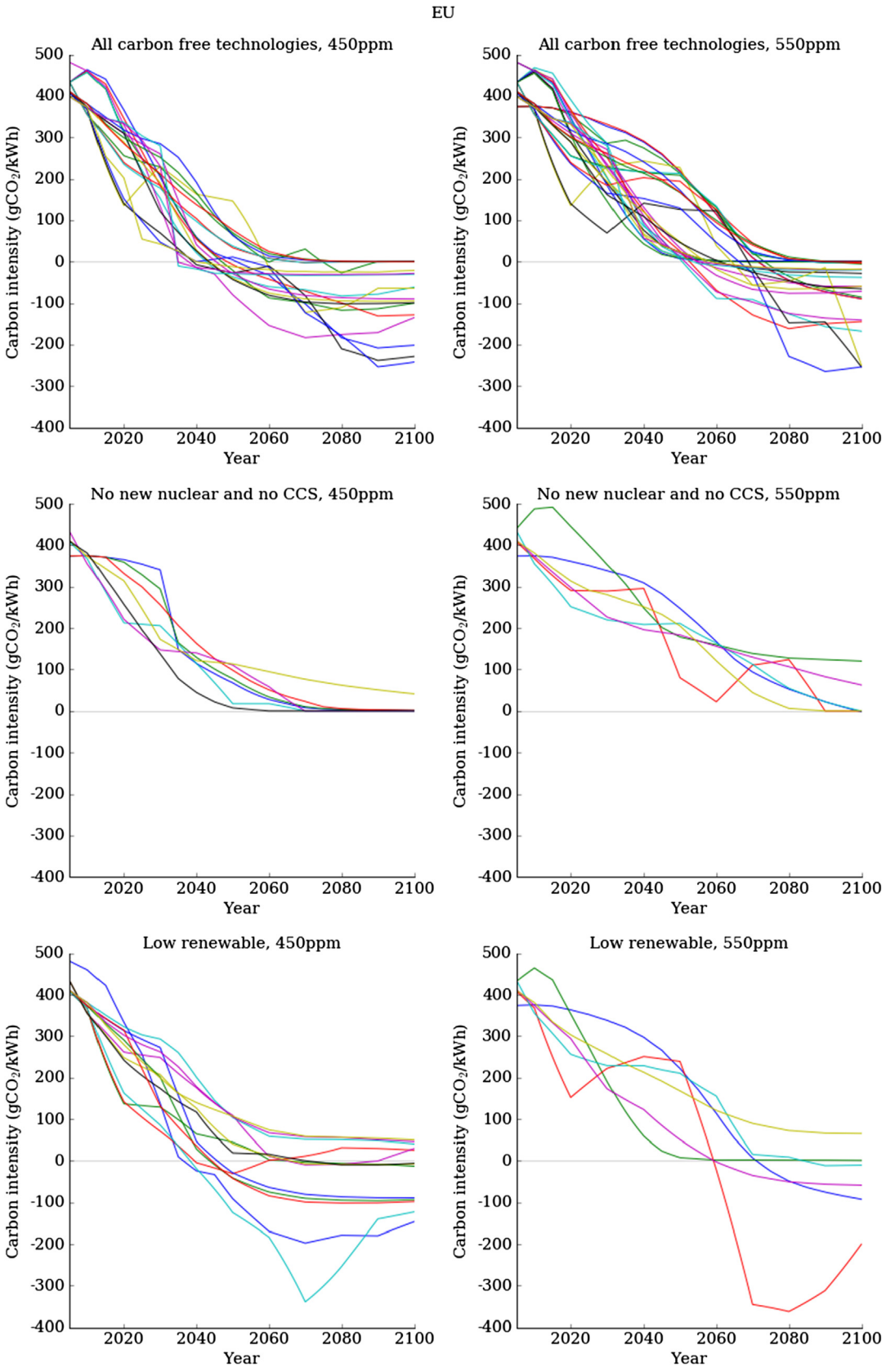

Fig. 7. Carbon content of electricity in the EU (AMPERE database).

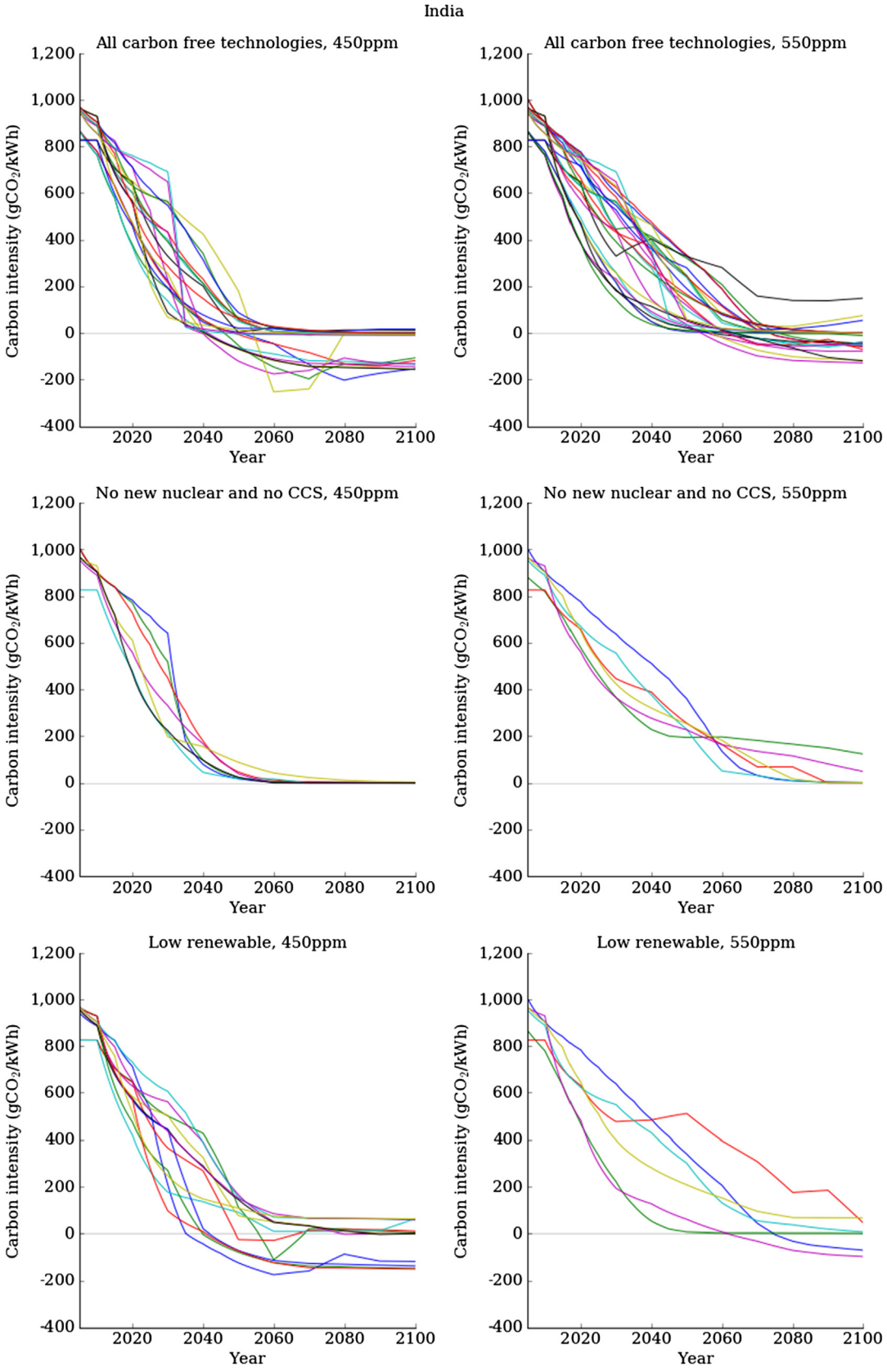

Fig. 8. Carbon content of electricity in India (AMPERE database).

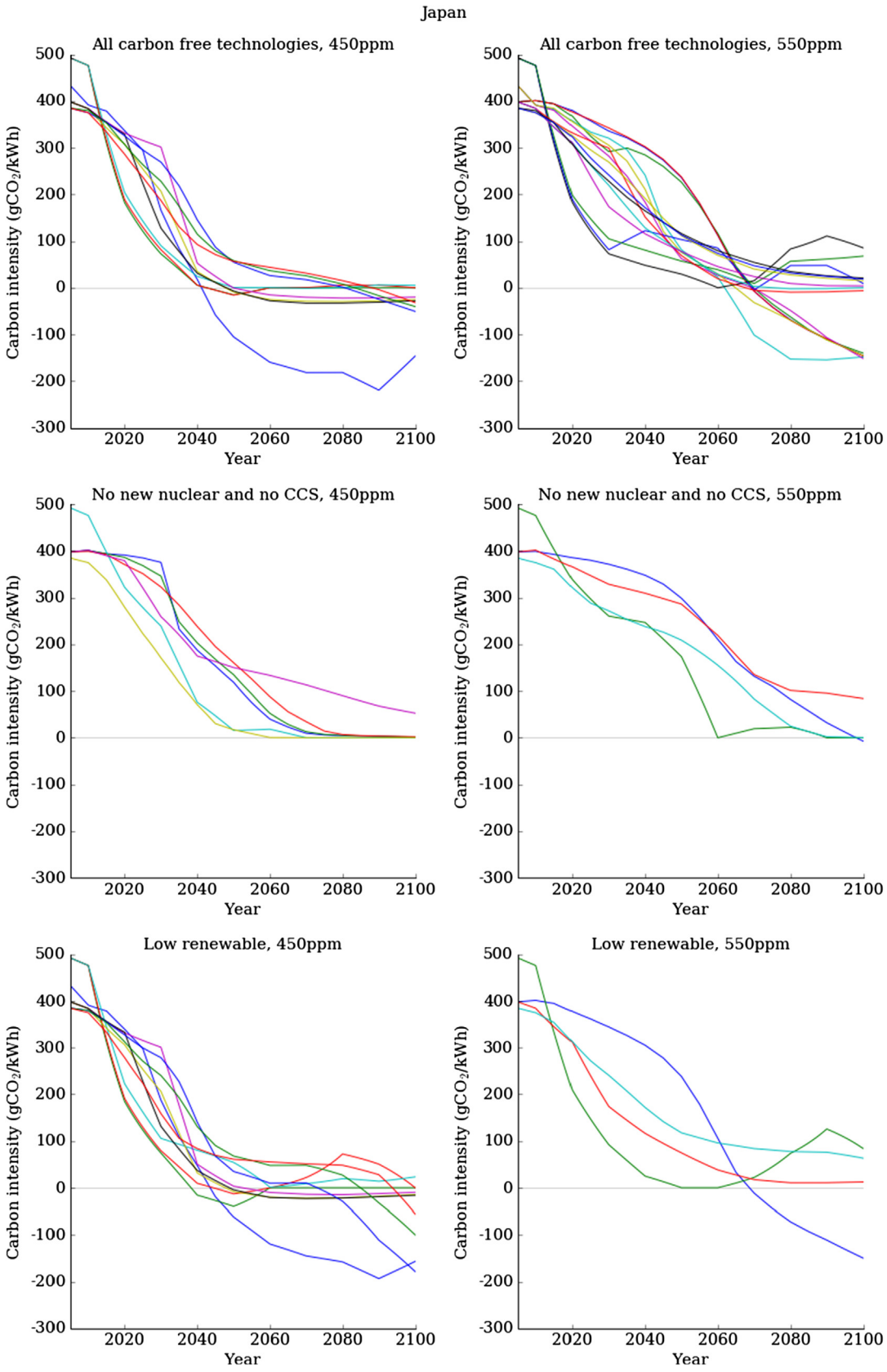

Fig. 9. Carbon content of electricity in Japan (AMPERE database).

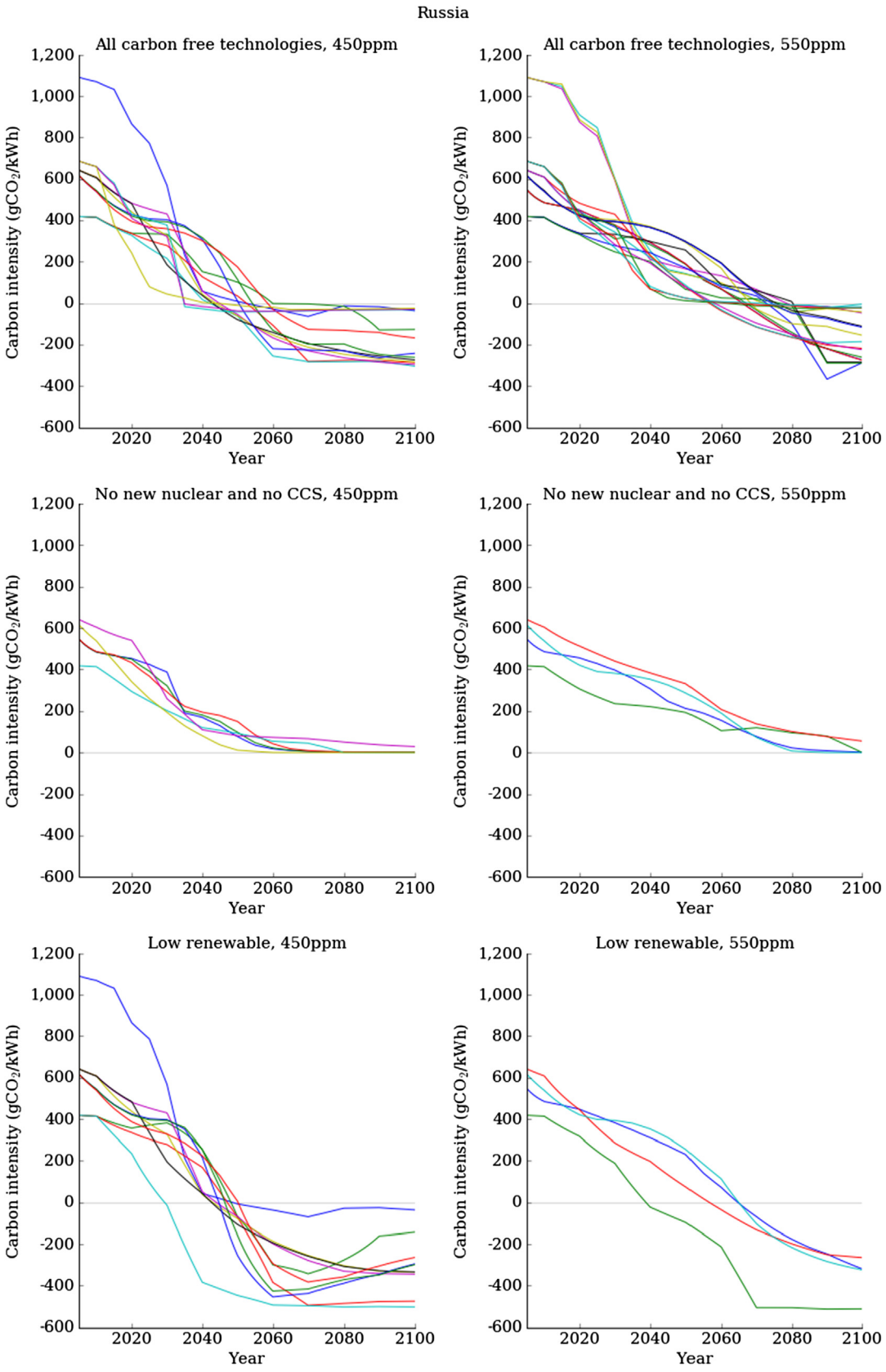

Fig. 10. Carbon content of electricity in Russia (AMPERE database).

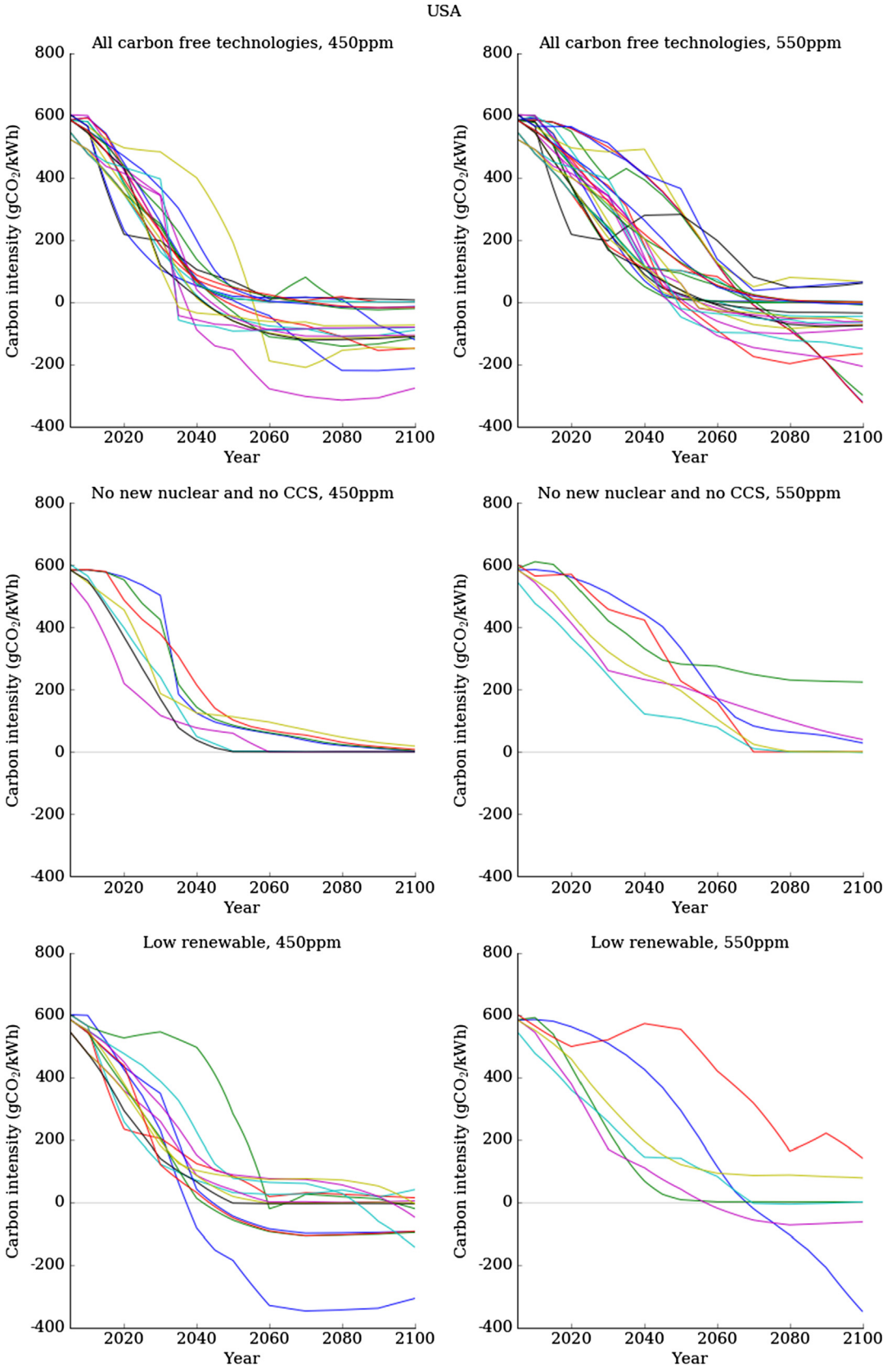

Fig. 11. Carbon content of electricity in USA (AMPERE database).

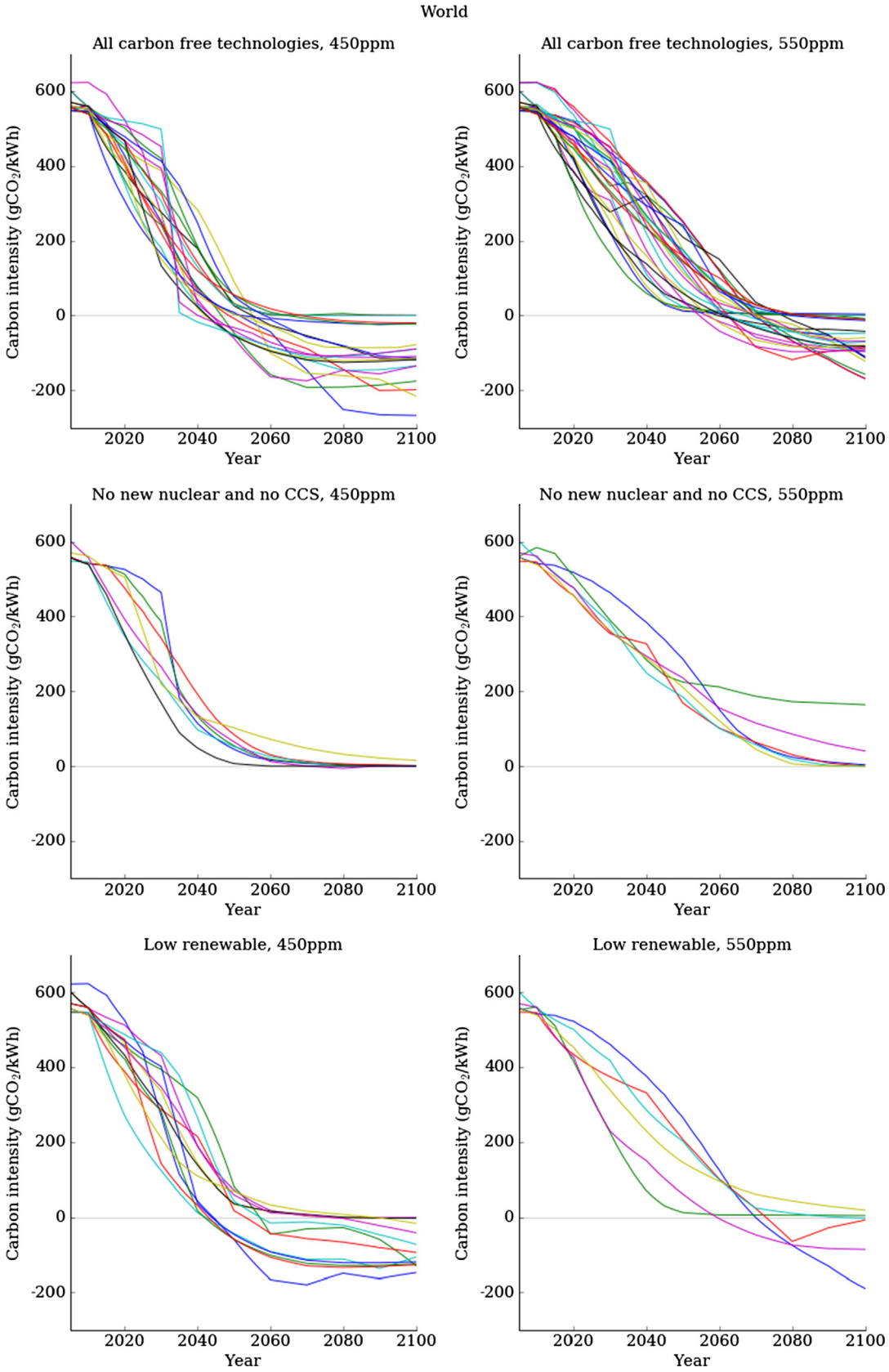

Fig. 12. Carbon intensity of electricity at the global level (AMPERE database).

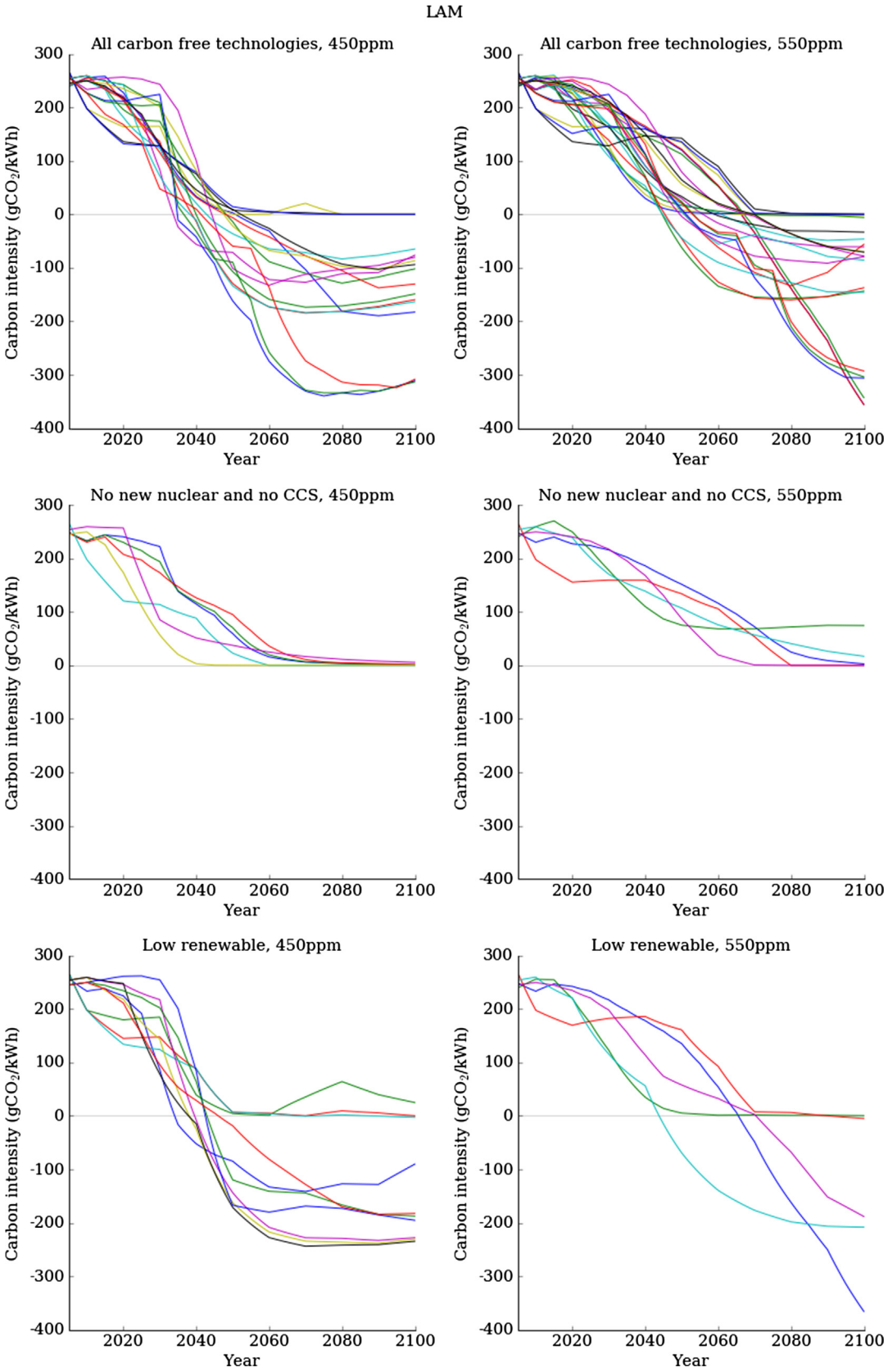

Fig. 13. Carbon intensity of electricity in Latin America and the Caribbean (AMPERE database).

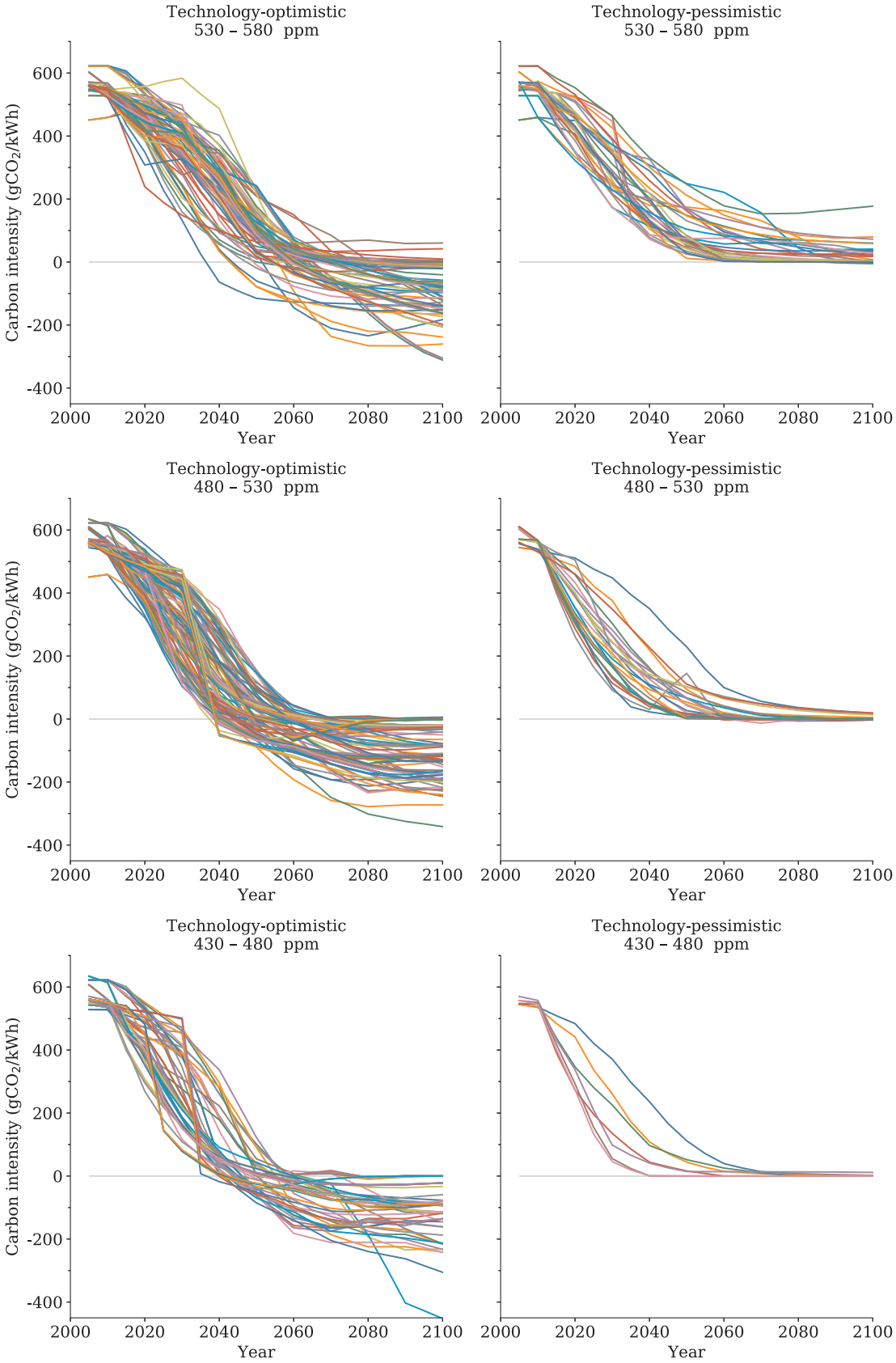

Fig. 14. Carbon intensity of electricity under different GHG concentration targets in 2100 and different technology assumption at the global level from IPCC AR5 database [45].

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